Journal of Power Sources, 29 (1990) 181 - 192

POSSIBLE FUEL CELL APPLICATIONS FOR SHIPS AND SUBMARINES*

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Introduction

Fuel cells chemically convert fuels into direct current electrical energy and unlike heat engines, are not limited by the Carnot cycle. Although still an emerging technology, small and high reliability fuel cell plants have been built for space applications and large systems as demonstrators for commercial power generation [1]. In these applications automatic and reliable operation of fuel cells has been demonstrated.

Military applications have included small land based systems using phosphoric acid electrolyte fuel cells [2, 3] and a German development using alkaline electrolyte fuel cells in a submarine [4, 5].

For the operation of a fuel cell system, fuels generally have to be converted to usable hydrogen which is combined with oxygen in the fuel cell to produce water and electric power through a load. The following summarises benefits which might accrue from applying fuel cell systems to surface ships and submarines, and is based on earlier papers [6, 7].

Advantages and disadvantages

The advantages of replacing diesel-generators with fuel cell systems are seen to be:

(a) high efficiency (50% to 65% compared with 25% to 35% for a diesel-generator) resulting in increased endurance

(b) lower noise output (no moving parts except for pumps for fuel/air supplies) and IR signature

(c) lower running and maintenance costs with a significant increase in the mean time before module replacement compared to diesel electric generators

(d) savings in weight

*This paper expresses the views of the author which do not necessarily represent those of his department.

Elsevier Sequoia/Printed in The Netherlands

(e) direct generation of d.c. for supply to low/medium speed electric propulsion motors

(f) the ability to disperse fuel cell generators where required throughout the vessel

(g) a preliminary estimate indicates that there is no increase in through-life costs when compared with diesel-generatores.

Operational advantages in terms of broad operational requirements are therefore seen to be:

(a) reduced fuel consumption because of increased efficiency

(b) lower noise signature output because of fewer moving parts and a lower IR signature because of lower exhaust temperature and less waste heat

(c) increased endurance because of lower fuel consumption

(d) lower manning requirement because of installation of automatically controlled system and reduced maintenance

(e) lower support costs (running and maintenance), because of installation of modular system

(f) increased availability because of increased reliability

(g) increased battle survivability because of dispersion of fuel cell generation throughout the ship

Disavantages of fuel cell systems are seen to be:

(a) new development and higher procurement costs than diesel-generators (approx. three times for procurement)

(b) the need for d.c. to a.c. conversion for auxiliaries

(c) in the case of submarines, the need to dispose discreetly of waste products such as water, heat and (for reformed fuels) carbon dioxide,

(d) the need to demonstrate the ability to reform diesel fuel into gases suitable for use with fuel cells

(e) possible difficulties in the operation of reformers and fuel cells; depending upon the design, these may both need to be modularised and one or more modules run at full power to achieve variation in the output.

Submarine systems

Submarine application requires the vessel to carry both fuel and oxidant which can readily be used by the fuel cell system or converted to hydrogen and oxygen before being used.

A submarine system based on metal hydride and liquid oxygen stores has been developed in the F.R.G. [4] and a prototype auxiliary system capable of generating 100 kW fitted into an extended type 201 (U1) for the Federal German Navy [5].

Fuel cell technology and performance is very dependent on the type of fuel cell as well as the type of fuel and oxidant used. Studies [6] have indicated that cells using either proton exchange membrane (PEM) electrolyte or alkaline electrolyte will best meet a submarine's needs primarily due to high power density, low temperature operation and fast start-up times, PEM being the preferred option. Some developments in fuel cells [8, 9] confirm this. Other studies [10, 11] show a different conclusion, *i.e.* that molten carbonate electrolyte cells would be advantageous.

The choice of fuel for underwater vehicle storage is wide; for example, hydrogen, alcohols, hydrocarbons, hydrazine or ammonia could be used. However, some are very reactive or expensive and the final selection depends on such criteria as reactivity and method of storage, or whether reforming is possible to produce a fuel useable in fuel cells.

Since submarines spend only a small amount of their running time at full speed it is assumed that it would not be cost effective to install large power fuel cells for this purpose. Thus, batteries would be retained for high speeds and, depending upon the installed fuel cell power, diesel-generators may be needed for battery recharging.

In order to obtain maximum efficiency the choice of oxidant is limited to gaseous or liquid oxygen, or chemicals such as peroxides or heavy metal oxides which can produce oxygen by dissociation. Table 1 lists data for oxidant and fuel stores which are considered to be the most practicable and cost effective.

TABLE 1

Fuel and oxidant data relative to overall storage space available

Fuel	Oxidant	Possible type of stowage	Store	
			kg O_2/m^3	kg H_2/m^3
Diesel		tanks		280
Methanol		outboard flexible containers or tanks		100
Hydrogen		solid metal hydride		10 to 25
	HTP	outboard flexible containers	440	
	O_2(l)	cryogenic tanks	100 to 350 (depends on pressure)	

To compare the various combinations of fuel and oxidant Fig. 1 shows the benefit, in comparative terms only, to the submerged endurance that might be obtained for a typical conventional (non-nuclear) patrol submarine of two to three thousand tonnes displacement. The variation in endurance at patrol speeds against overall stored volume of the various combinations of fuel and oxidant is illustrated. Typical endurances for a lead/acid battery

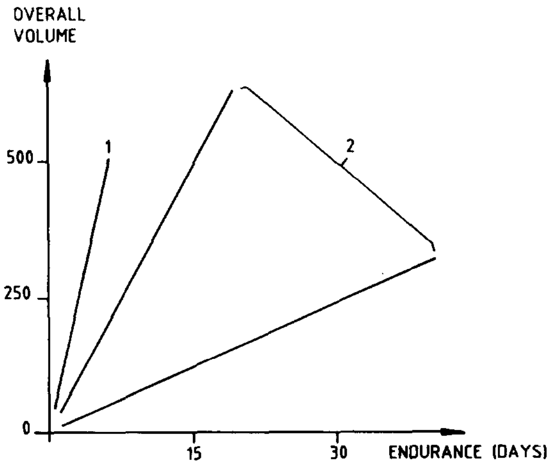

Fig. 1. Variations of volume/endurance dependent on fuel + oxygen combination: 1, lead acid battery; 2, fuel cell plant.

are also illustrated for comparison. By a suitable choice of fuel and oxidant a significant improvement in underwater endurance is possible with fuel cell systems.

Surface ship systems

Surface ship applications are even more favorable than in submarines because on oxidant for the fuel cell does not have to be carried and the disposal of waste products such as carbon dioxide and water does not present a problem.

It is considered to be impracticable to use fuel cell systems for the generation of sufficient power to drive large ships at their maximum speed. Thus, in these cases, application is confined to replacing on board diesel-generators used for power generation and low to medium electric ship drives, whilst the existing prime movers, such as gas turbines, are retained for the higher speeds. Hence, for surface ship application it would be highly desirable to employ fuel cells which can readily operate on diesel oil reformate, ideally assumed to be a mixture of hydrogen and carbon dioxide, as a fuel and air as an oxidant. This would require the use of onboard diesel reformers.

Several types of fuel cell could be developed for surface ship application, but considerations here will be mainly restricted to those which are furthest advanced, can readily use diesel oil reformate as a fuel and air as an oxidant. Marine fuel such as diesel oil would need to be reformed into a reformate consisting ideally of a mixture of hydrogen and carbon dioxide which could be used directly in the fuel cell stacks. Other suitable types not yet fully developed will be mentioned briefly.

The above criteria limit us in the short term to:

(a) phosphoric acid fuel cells (PAFC), which can operate from reformed fuel and are carbon monoxide tolerant

(b) solid polymer fuel cells (SPFC), also known as proton exchange membrane fuel cells (PEMFC), preferred due to their higher power density and fast start-up times, except that they are poisoned by carbon monoxide.

Other longer term development possibilities [1, 10] are molten carbonate fuel cells (MCFC) or solid oxide fuel cells (SOFC) and these offer the possibility of using integrated reformers because of their higher temperature of operation. The PAFC, SPFC and MCFC types would require the diesel fuel reformate to be desulphurised, whereas SOFC may be more tolerant to sulphur.

PAFC have been widely tested in land based demonstrators varying in power output from 40 kW to 4.5 MW and using reformed natural gas as a fuel [1]. However, PAFC are no longer receiving large funding for utility demonstration. SPFC with power output up to 5 kW have been built and larger cell stacks are being developed. Solid polymer electrolyte technology is also employed for electrolysers.

MCFC power plants are now receiving major electric utility development and demonstration funding in the U.S.A., Japan and Europe, leading to multimegawatt power level plants in the mid 1990s.

When considering the most suitable types of fuel cell, existing data are only available for PAFC and small SPFC. Data on 20 kW MCFC laboratory prototypes are also available. Figure 2 gives estimated variations of fuel cell system sizes, including reformers, compared with typical diesel-generators. Reformer parameters are more difficult to estimate than those for the fuel cell stacks and in Fig. 2, are based on land demonstrator units built for natural gas. Figure 3 gives estimated weights for fuel cell stacks only, compared with diesel-generators.

Estimated diesel oil consumptions for fuel cells are shown in Fig. 4 compared with diesel-generators. The data for fuel cells is based on the steam reforming of diesel oil into carbon monoxide and hydrogen followed by a water gas shift reaction to produce further hydrogen and carbon dioxide with an overall 90% conversion efficiency. Dodecane ($C_{12}H_{26}$) is assumed as a suitable model for diesel oil, but the choice of other hydrocarbons as a model would not change the results significantly.

In order to give some indication of fuel cell system module sizes, estimated outlines of cell stacks and reformers for surface ship application, based on known commercial developments and proposals, are shown in Fig. 5, together with typical outlines of diesel-generators. A possible schematic layout for a 1.4 MW SPFC system is shown in Fig. 6 compared on the same scale with a typical surface ship 1.3 MW diesel-generator in its housing. A volume for a 1.4 MW MCFC system based on published data [11] is also given for comparison.

It is not possible at this stage to compare complete installations of comparable power output.

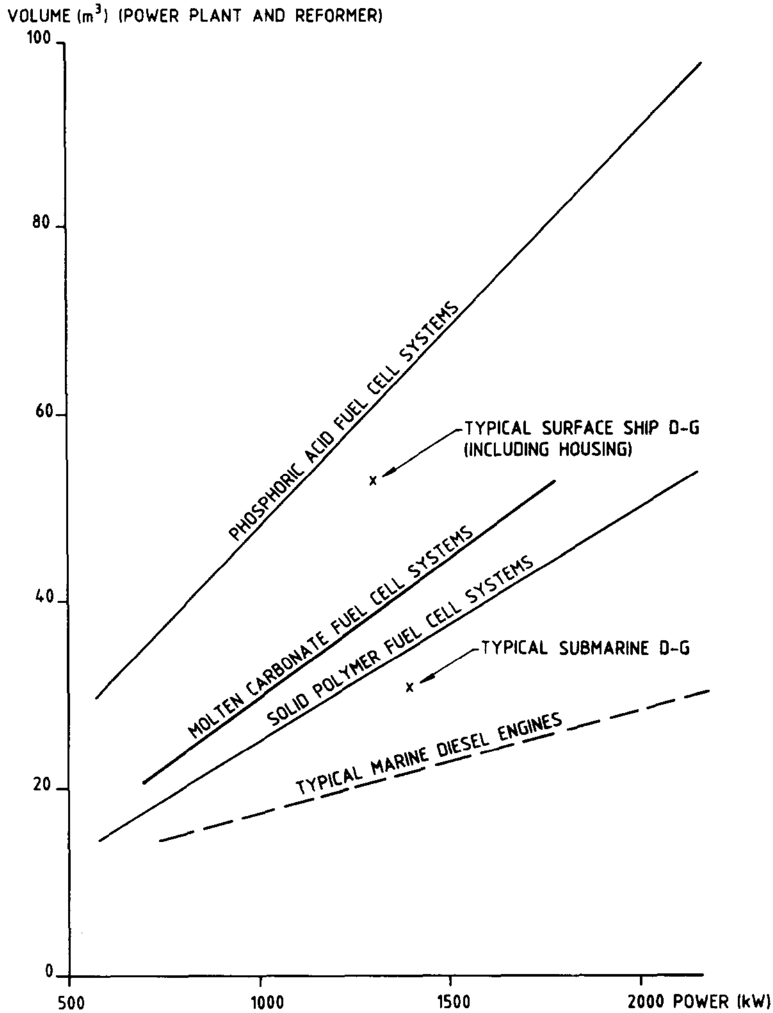

Fig. 2. Estimated volumes.

System engineering

Individual fuel cells must be combined into stacks and it has been identified that careful attention needs to be paid to the control of fuel, waste products and power management for any system to be successful. Fuel cells are readily assembled into stacks and stacks into modules and this has been successfully achieved for PAFC systems up to 4.5 MW [1]; technical risk is predominantly associated with system management. The risk involved in scaling up SPFC from the present 5 kW to larger modules for use in practicable systems is therefore assessed as low. A 50 to 100 kW

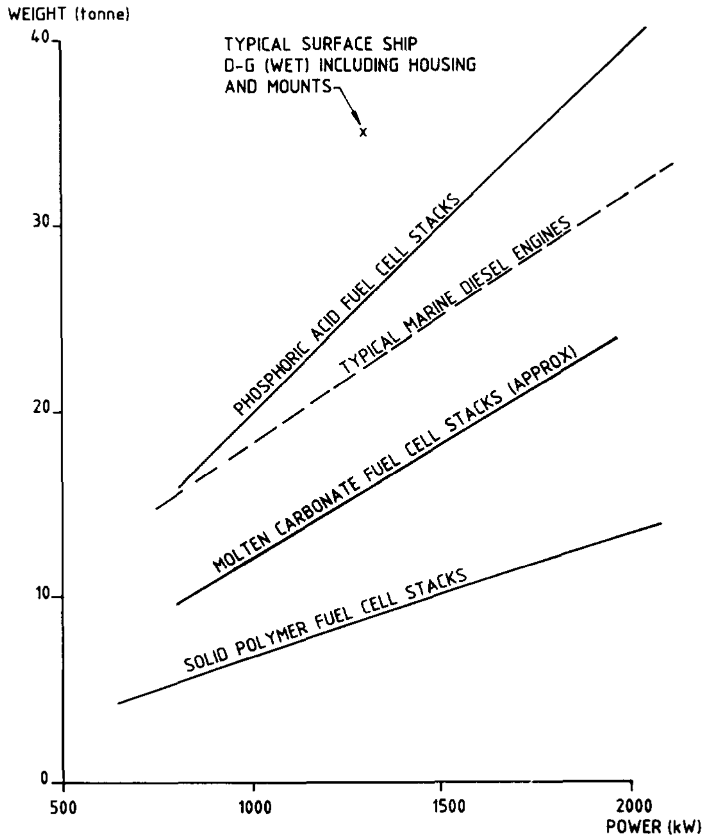

Fig. 3. Estimated weights.

module is the minimum thought to be suitable for building up into systems in excess of 1 MW.

In order to power surface ship auxiliary systems it would be necessary either to convert these to d.c. or, as is more likely, to provide d.c. to a.c. conversion equipment. Solid state d.c. to a.c. conversion equipment has been successfully demonstrated with fuel cell systems built as demonstrators for commercial power generation [1] and no problems are envisaged.

For submarine operation where a battery installation is retained it would be necessary to install a d.c. to d.c. power conditioner if the batteries are to remain connected during fuel cell operation.

Liquid fuels such as alcohols and hydrocarbons may be reformed to produce a reformate gas consisting ideally of hydrogen and carbon dioxide. This reformate may be fed to the fuel cells where the hydrogen combines with oxygen to form water and usable power is produced. In practice the fuel process involves steam reforming to produce carbon monoxide and hydrogen followed by a water gas shift reaction (using steam) to produce further hydrogen and carbon dioxide, *e.g.*

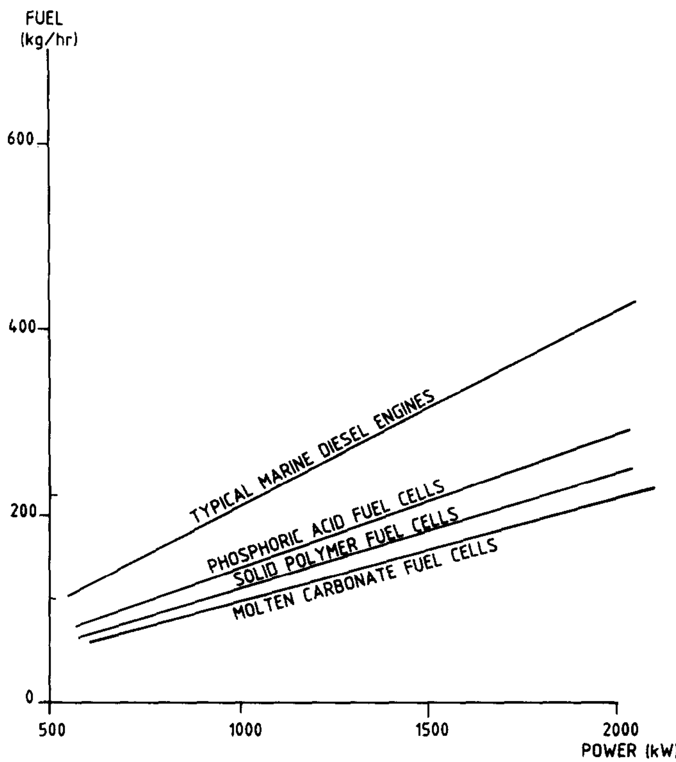

Fig. 4. Estimated fuel consumptions.

(a) $CH_3OH = CO + 2H_2$ and $CO + H_2O = CO_2 + H_2$ with an overall reaction of $CH_3OH + H_2O = CO_2 + 3H_2$ for methanol

(b) $C_nH_{2n+2} + nH_2O = (2n + 1)H_2 + nCO$ and $nCO + nH_2O = nCO_2 + nH_2$ with an overall reaction of $C_nH_{2n+2} + 2nH_2O = (3n + 1)H_2 + nCO_2$ for a hydrocarbon such as diesel fuel.

Steam reforming involves the use of steam and hence feed water. However, each mole of hydrogen produced from the fuel reacts with oxygen in the fuel cells to produce a mole of water. Thus, if the water requirement per mole of hydrogen produced is less than unity then the fuel cells can provide water both for reforming and other purposes.

Methanol requires less water than other candidate fuels with more water being required with increase in carbon number: based on stoichiometric reactions, water needed/mole hydrogen produced is 0.33 for methanol and 0.65 for $C_{12}H_{26}$ (an assumed model for diesel oil). In practice however, except for methanol, it is necessary to conduct the reaction in an excess of steam in order to suppress the deposition of carbon onto the catalyst used in the reforming process. (Methanol is unusual in that no excess steam is required because it readily thermally decomposes into carbon monoxide and hydrogen which does not lead to carbon deposition.) Thus, unless the

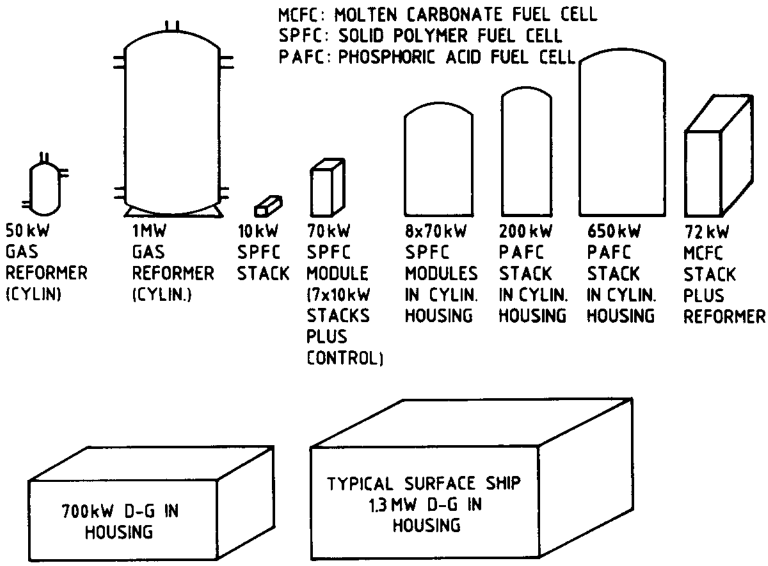

Fig. 5. Estimated overall sizes to same scale.

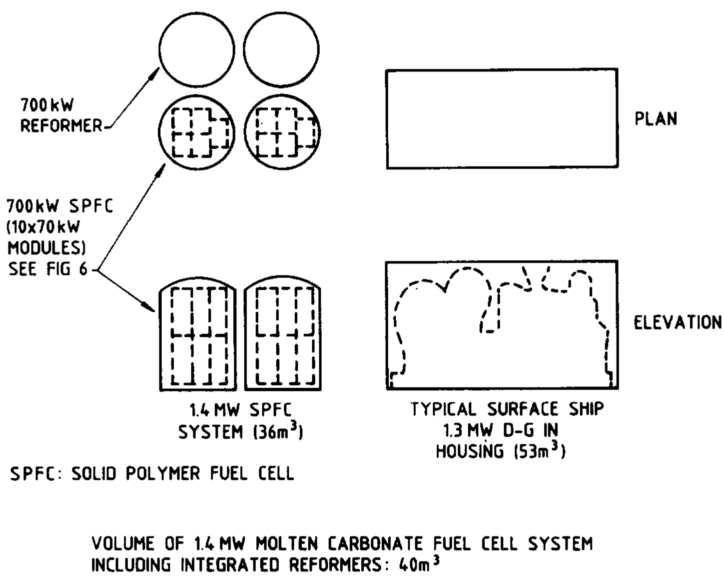

Fig. 6. Possible schematic layouts to same scale.

excess is removed downstream more will be required than is produced by the fuel cells.

Problems associated with diesel oil are the possible, but unlikely, presence of additives in readily available products that could poison the catalysts used in the reformer and the presence of sulphur.

Desulphurisation of the diesel oil is necessary to avoid poisoning the fuel cell catalyst and this possibly could be achieved after the steam reforming reaction by hydrogenating the sulphur compounds using some of the product hydrogen, thus removing the sulphur as hydrogen sulphide. The only candidate for the direct reforming of diesel oil (internally to the fuel cell system) without desulphurisation is the solid oxide type of fuel cell, although SOFC are not as sulphur tolerant as a diesel engine.

The U.S. DOD have funded work on reformers for diesel oil (not a marine application) [12]. This programme, for the USAF, included the demonstration of processes (including desulphurisation) capable of converting diesel fuel to fuel cell quality hydrogen for low power plants (less than 50 kW). Three demonstrators were funded in 1985 (Energy Research Corp. (ERC), International Fuel Cells (IFC) and R. M. Parsons Co. (RMP)) and run, although the IFC version failed after 20 h. The ERC plant employed desulphurisation followed by steam reforming and completed 400 h of satisfactory performance. The RMP plant used steam reforming followed by autothermal reforming and sulphur removal; this demonstration was inconclusive due to 'mechanical problems' but the process was considered to be a viable contender [12].

Compact gas reformers for PAFC are normally of tubular construction but these have the disadvantage that they are difficult to moderate in response to load changes. The reformer tubes are more liable to cause incomplete combustion (and hence carbon monoxide in the reformate gas) the smaller the size becomes, abnormal temperatures can occur in them in the event of load changes and the catalyst can become broken and choked up by lodgement.

More recently [13] a new plate type design of reformer under development in Japan is aimed at the improvement of reformer response to load changes and integration with high temperature fuel cells such as the MCFC type. The heat transmission and reaction mechanisms, and control of the gas temperature have been successfully demonstrated in a catalyst-filled plate reformer. It would be advantageous if this type of construction could be applied to diesel oil reformers.

Thus, there is some technical risk involved with the reforming function for diesel oil. Additionally, some reforming processes cannot be readily moderated to provide fuel to the cells for the generation of intermediate power levels. However, it is envisaged that, like the fuel cell stacks, reformers could also be modularised to provide fuel to each 50 to 100 kW, or larger, fuel cell module. Carbon monoxide is difficult to remove, particularly when the reformer is required to operate over a wide range of power levels from idle to full power with rapid throttle response. New designs of reformer based on a plate type of construction [13], may alleviate this problem.

Estimated costs

In order to assess the relative through-life costs the following assumptions have been made:

(a) Support costs for fuel cell systems would be the same as those for diesel-generators (but in practice are almost certain to be less)

(b) Capital cost of a 1 MW fuel cell system is £2M

(c) Capital cost of a 750 kW diesel-generator is £500K

(d) Fuel costs over a 25 year ship life are based on a 30% usage and the specific fuel consumptions in Fig. 4.

Based on the above the through-life costs for a 1 MW output are approximately £5.6M for both diesel-generator and fuel cell systems.

Conclusions

In terms of power to weight ratio, fuel consumption and operational advantages, projected solid polymer electrolyte and molten carbonate electrolyte fuel cell systems are potentially more than competitive when compared with diesel-generators.

Although a detailed through-life costing exercise needs to be carried out, indications are that the total through-life costs for a fuel cell system would not exceed that for a diesel-generator fit. Against this however, it is necessary to offset the unknown development costs for marine fuel cell systems, including both cell stacks and diesel oil reformers.

The potential advantages that are seen to be offered by fuel cell systems, particularly low noise signature and reliable automatic operation are considered to outweigh the disadvantages. Areas of technical risk in developing fuel cells for surface ships are the problems associated with the steam reforming of diesel oil and overall system management.

In the longer term, molten carbonate fuel cells offer the possibility of incorporating an integrated diesel oil reformer. Solid oxide fuel cells, not yet beyond the early development stage, offer the possibility of directly reforming moderately sulphur-containing diesel oil internally, *i.e.* without total desulphurisation.

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